The Dynamics of Flux-Rope Coronal Mass Ejections

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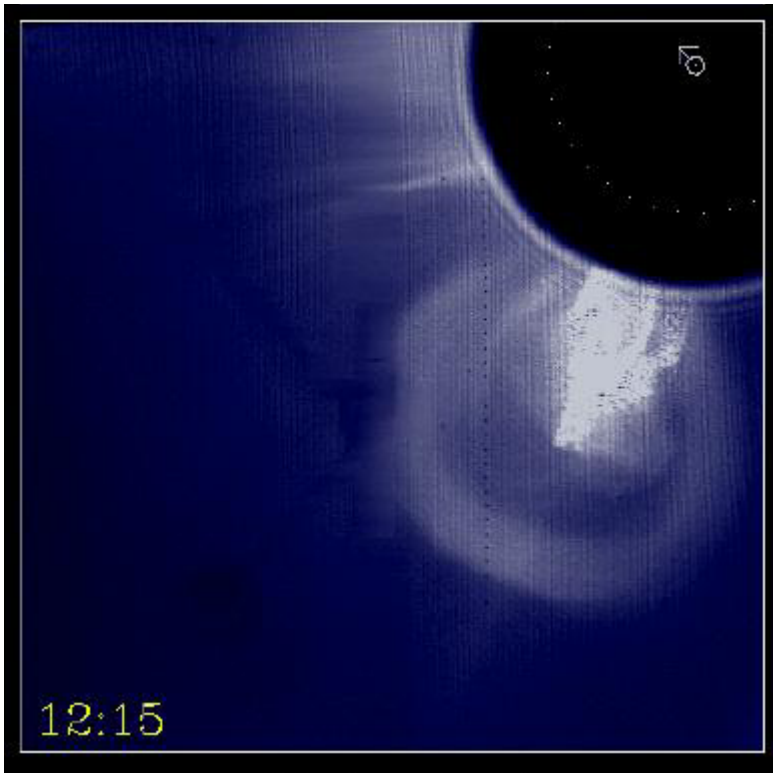
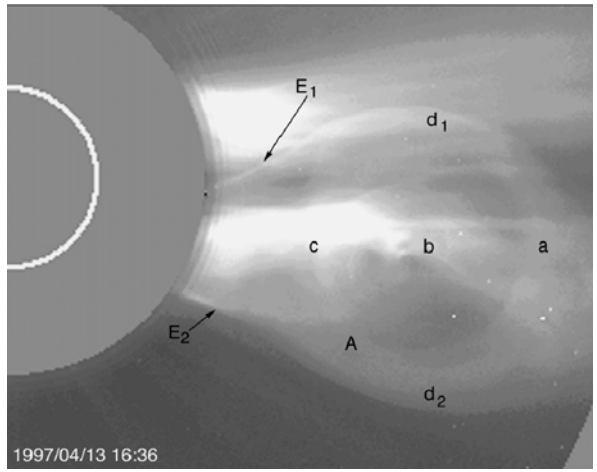
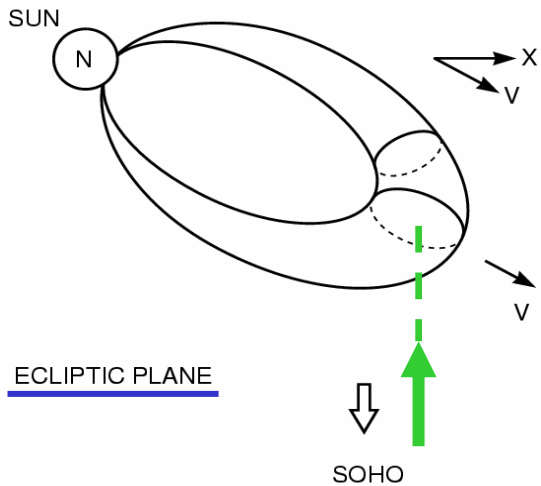
CME morphology: rim - cavity - prominence







Hypothesis: underlying magnetic structure is a flux rope.

Outline

I. Model-data comparisons support the flux-rope hypothesis

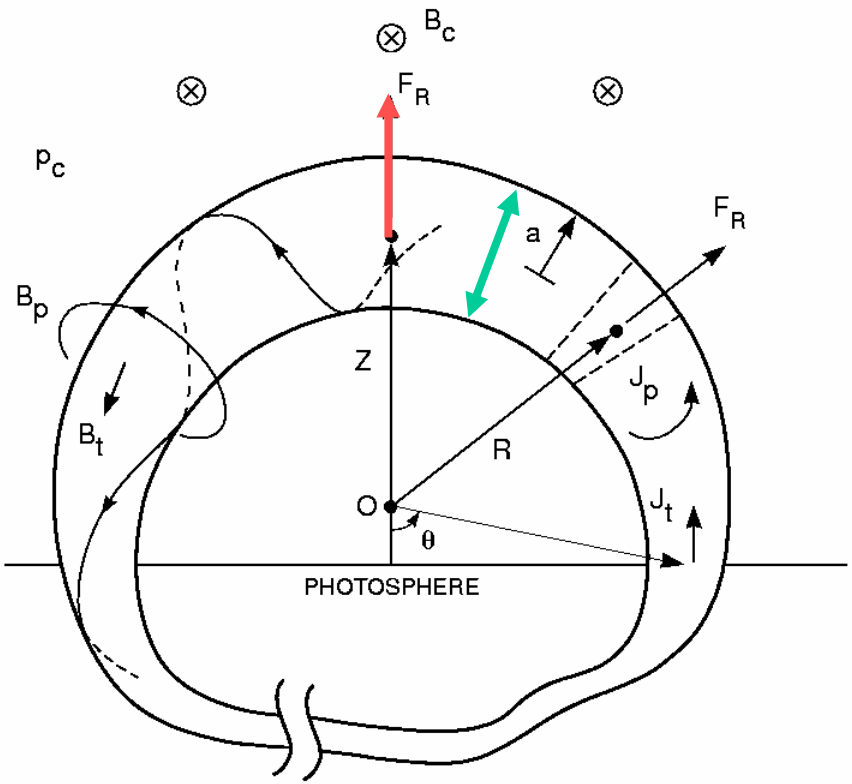
II. Near-sun CME dynamics – a universal acceleration profile

III. Flux-rope CMEs from the sun to 1 AU

IV. Macroscopic magnetic reconnection: is it needed?

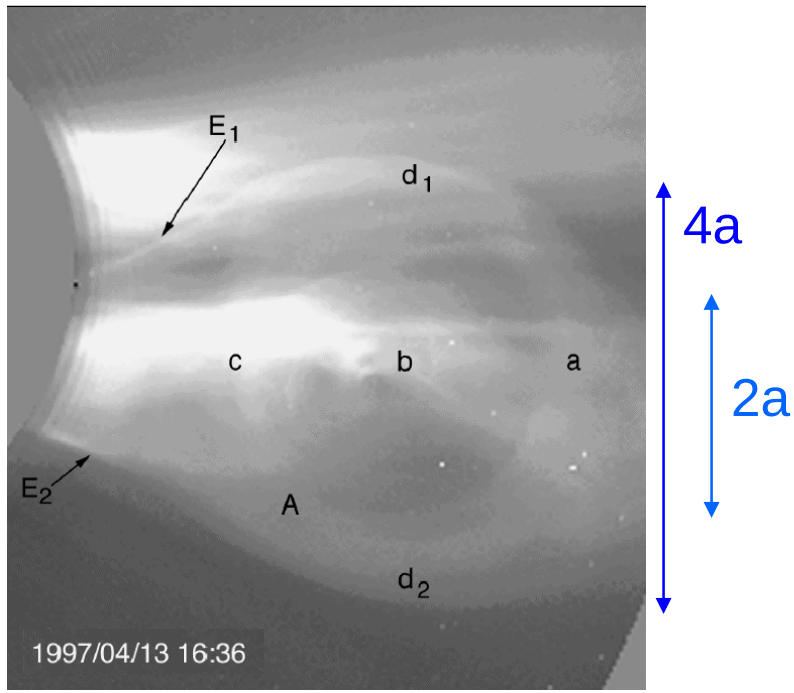
V. Summary

II. Model-data comparisons support the flux-rope hypothesis

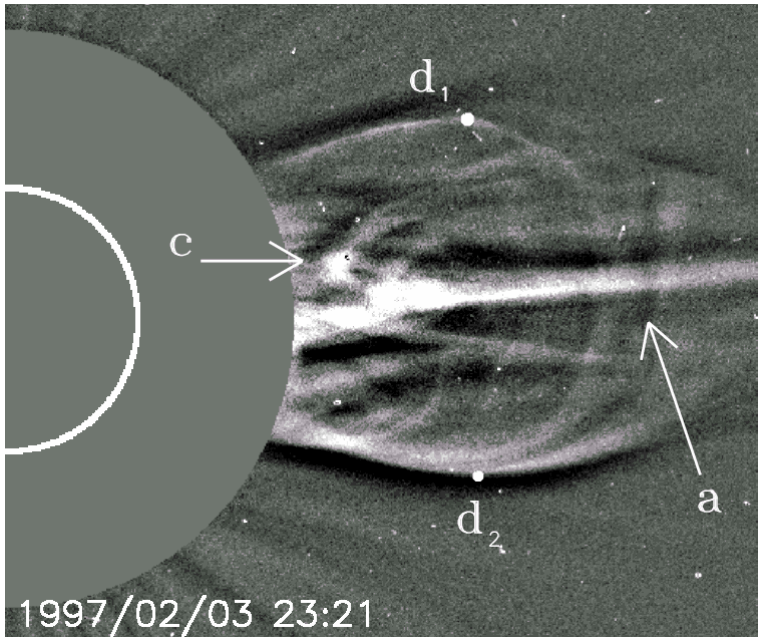


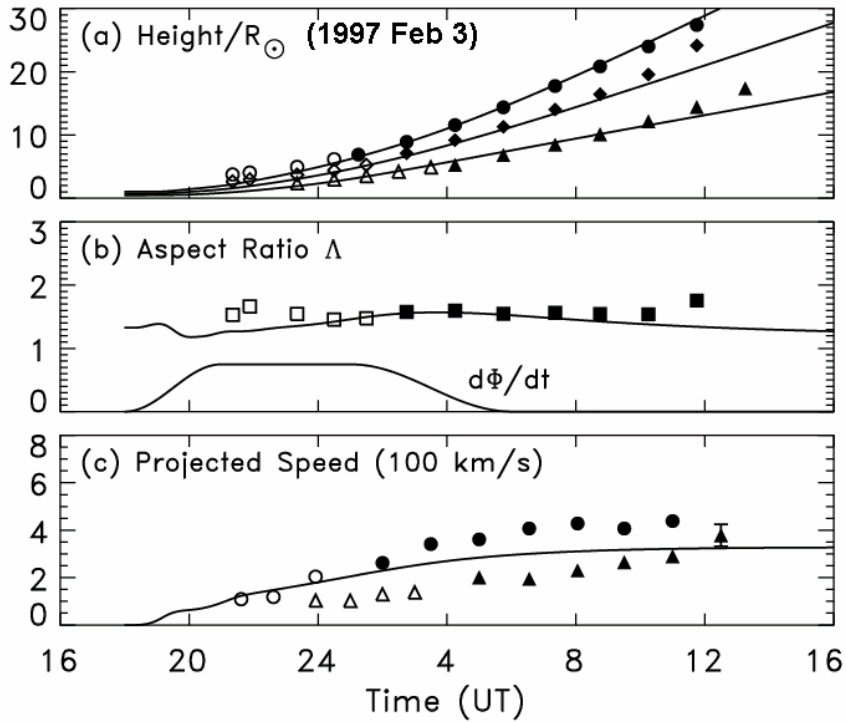
$$\frac{\partial^2 Z}{\partial t^2} = F[Z, a, \Phi_t, \Phi_p(t), \mathrm{SW}]$$
$$= F_{JxB} + F_{JxB_c} + F_P + F_g + F_d$$

$$\frac{\partial^2 a}{\partial t^2} = G[Z, a, \Phi_t, \Phi_p(t), \mathrm{SW}]$$



Chen 1996 JGR; Krall et al. 2000 ApJ



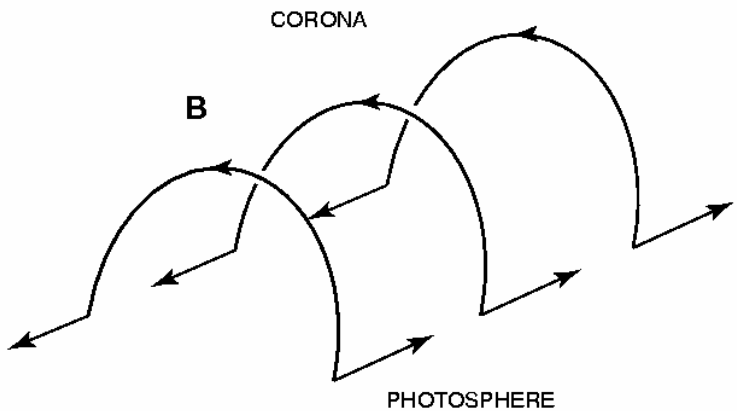


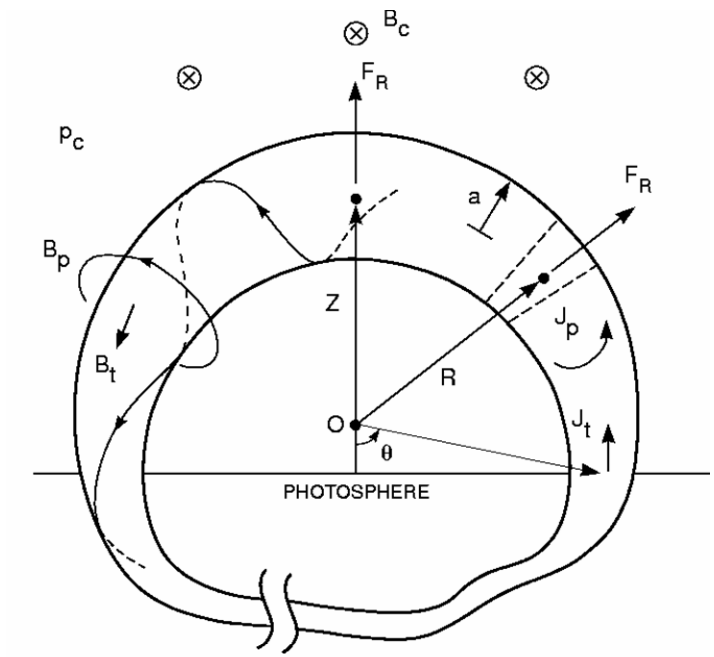
Background: we have measured CME position, aspect ratio, and velocity for many (>15) events.

For a model-data "match" all quantities must agree (and they do).

Chen et al., ApJ, 490, L191 (1997) Krall et al., ApJ, 562, 1045 (2001)

II. Near-sun CME dynamics – a universal acceleration profile





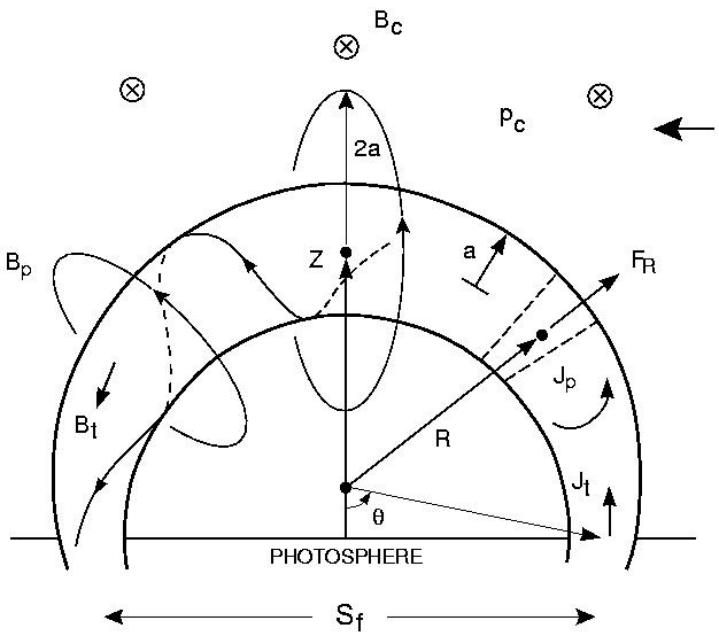
Magnetic arcade (e.g., Forbes and Priest 1995; Linker and Mikic 1995; Antiochos et al. 1999; Chen and Shibata 2000; Cheng et al. 2003)

Toroidal Magnetic flux rope (e.g., Chen 1989, 1996; Wu et al. 1999; Amari et al. 2000; Roussev et al. 2003; Manchester et al. 2004)

After the eruption, both scenarios lead to a flux rope

3-D Solar Magnetic Flux Ropes

- Major radial curvature $\kappa \equiv 1/R$
- Stationary foot points, separated by S_f
- Not present in arcades
- Not well-described by 2-D cartesian or axisymmetric models*



*Forbes and Priest 1995;
Wu et al. 1997;
Titov and Demoulin 1999;
Lin and Forbes 1999

Major Radial Force:

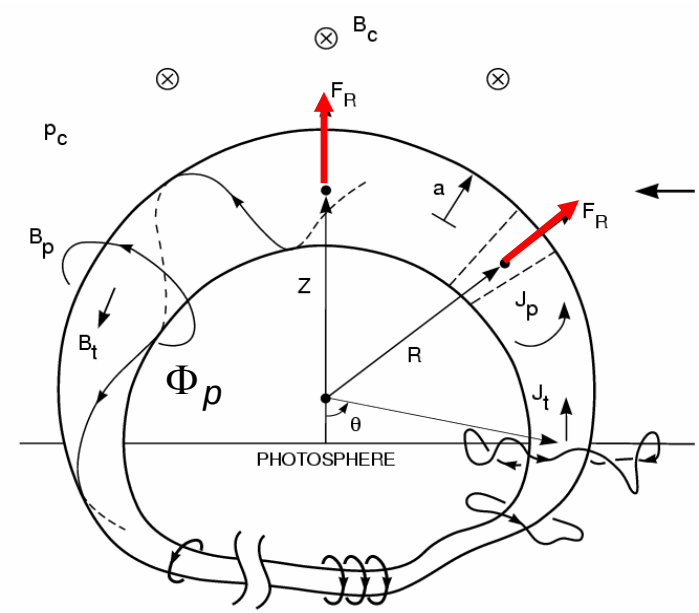
$$M\frac{d^2Z}{dt^2} = \frac{I_t^2}{c^2R}\underbrace{\left[\ln\left(\frac{8R}{a}\right)+\frac{1}{2}\beta_p-\frac{1}{2}\frac{B_t^2}{B_p^2}+2\left(\frac{R}{a}\right)\frac{B_c}{B_p}-1+\frac{\xi_i}{2}\right]}_{\equiv f_R}+F_g+F_d$$

$$\beta_p \equiv \frac{8\pi(\bar{p}-p_a)}{B_p^2}$$

Inductance of the Flux Rope:

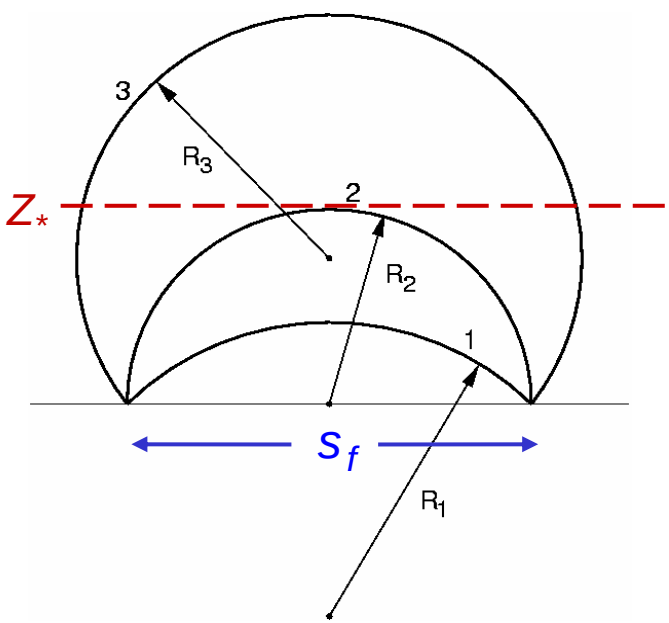
$$\Phi_p(t) \equiv cL(t)/I_t(t) \quad \rightarrow \quad \frac{\partial^2 Z}{\partial t^2} \propto \frac{\Phi_p^2}{L^2} f_R$$

$$L \propto R\log\left(\frac{8R}{a_f}\right) \quad \rightarrow \quad \frac{\partial^2 Z}{\partial t^2} \propto \frac{\Phi_p^2}{[R\log(R)]^2} f_R$$

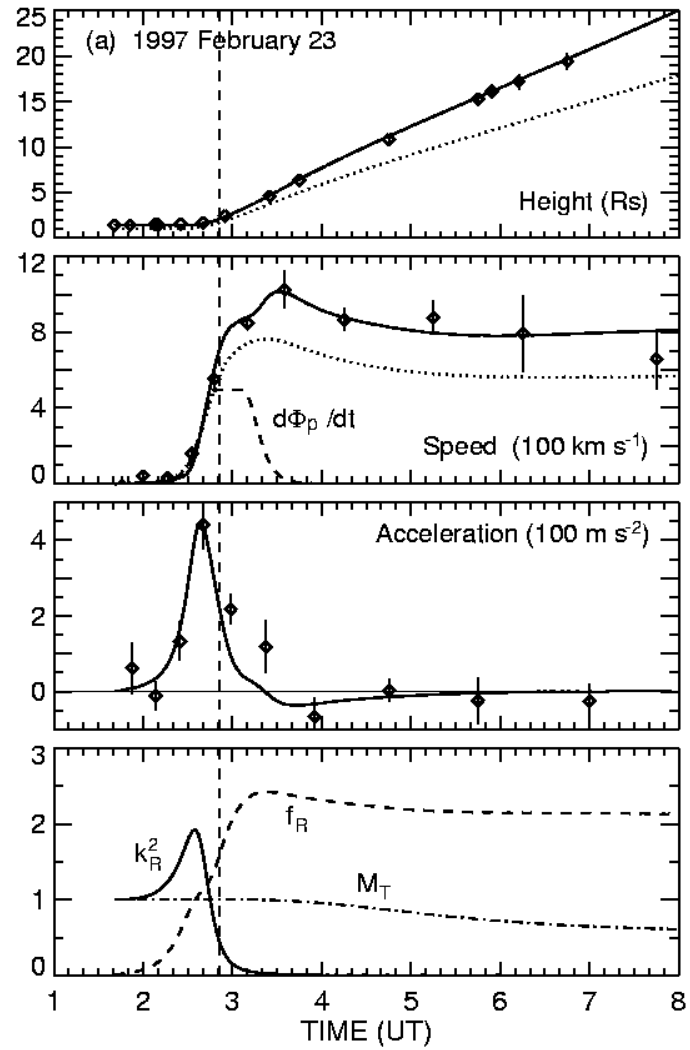


Force is maximum when the flux rope is semi-circular

$$F_{JxB} \sim \frac{\Phi_p^2}{R^2} f_R$$



$$Z_* = S_f / 2$$



Chen and Krall 2003 JGR

Critical Heights

Acceleration peaks at $Z_* = S_f / 2$

Main acceleration phase: $Z_* < Z < 2Z_*$

Direct consequence of 3-D toroidal flux rope with fixed foot points

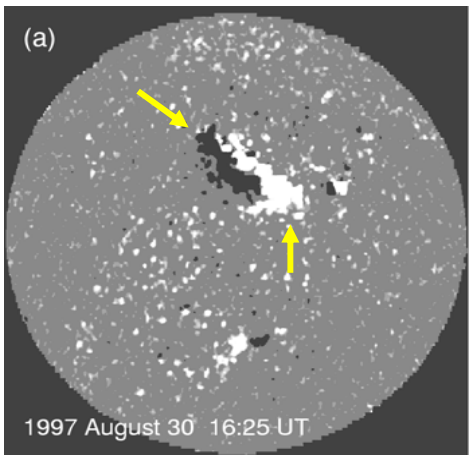
Universal scaling for erupting flux ropes

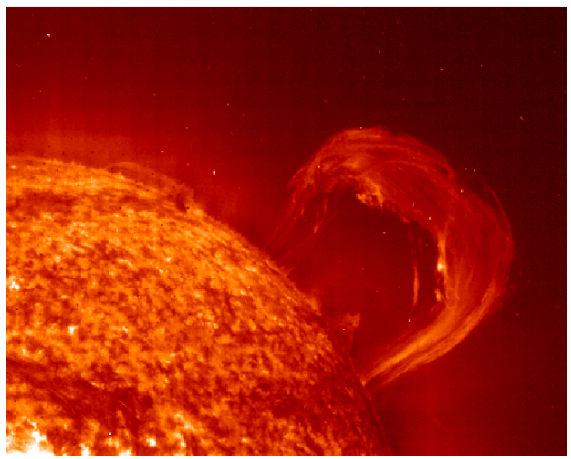
Key quantity: foot point separation S_f

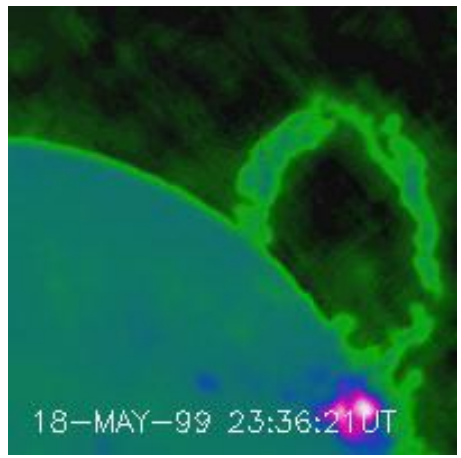
Foot point identification

As a proxy for magnetic footpoints, we use neutral line lengths and/or prominence legs in Hα, EIT, or radio data

Examples:



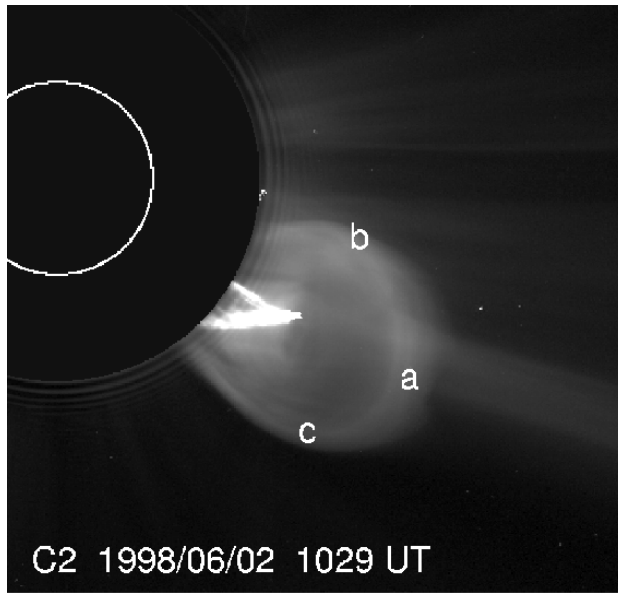




Look for limb events (both EPs and CMEs).

Measure footpoint separation distance and height-time Z(t) data

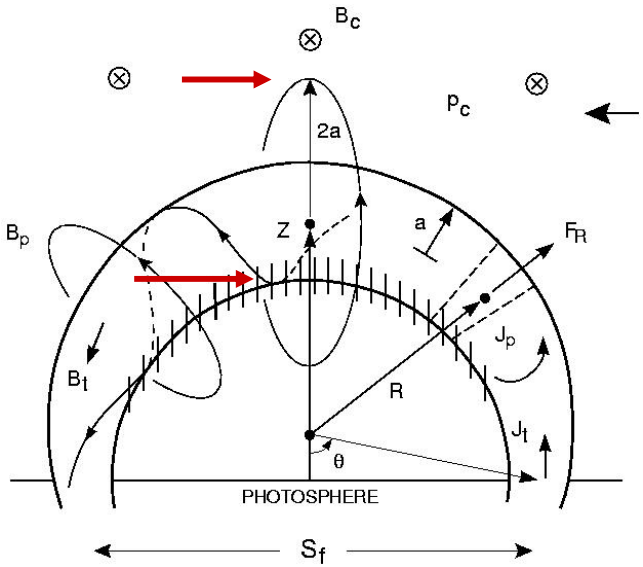
Flux-Rope Identification



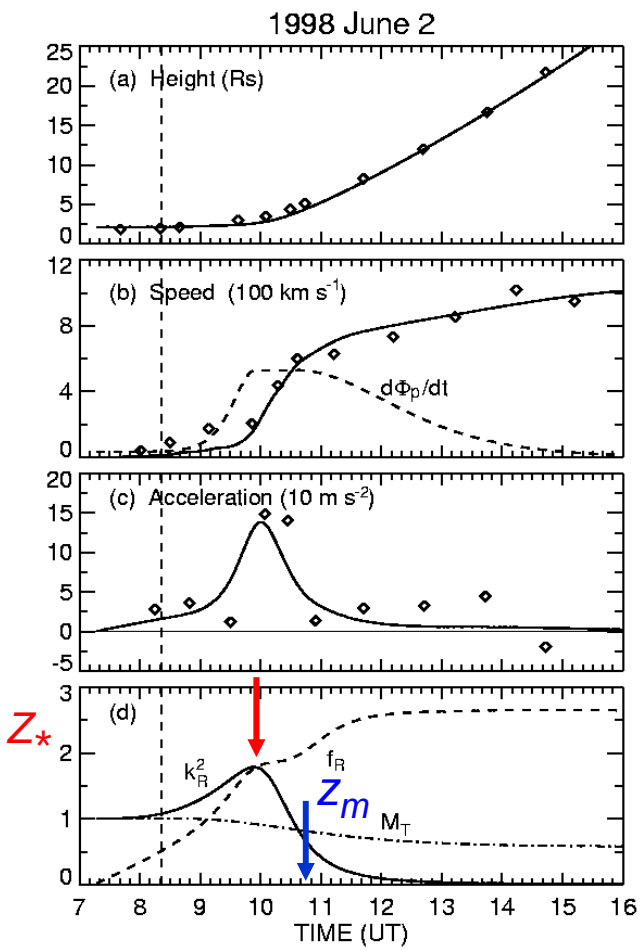
Observables:

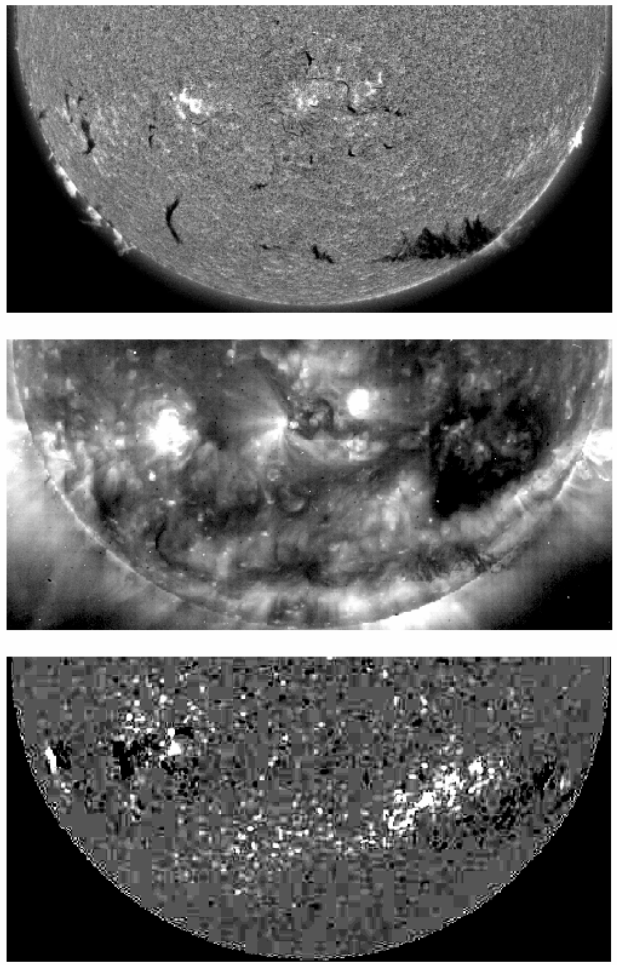
CME leading edge: Z + 2a

Prominence leading edge: Z - a

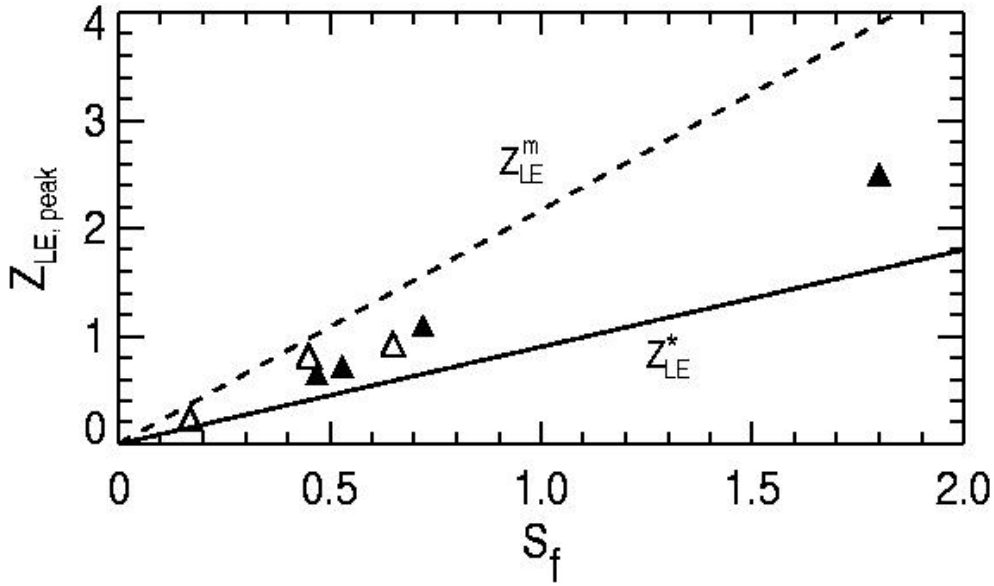


Example: 1998 June 2 CME



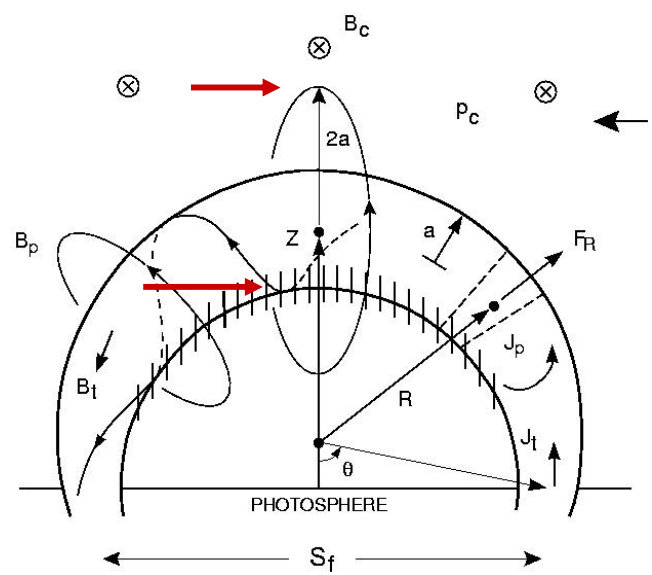


Results – near sun acceleration



▲ *Sf* determined by neutral line length

△ *Sf* determined by prominence legs



The flux rope is pre-existing or forms early in the process

Discussion - near sun flux-rope acceleration

The erupting structures were flux ropes prior to acceleration

Implications for “arcade-to-flux rope” scenarios:

- The flux rope must form well before peak acceleration
- No arcade model has predicted this scaling law
- Arcade behavior not yet known in a quantitative way

Numerical Simulations:

- Roussev et al. (2003) in excellent agreement

  (see Chen and Krall, JGR, 2003)

Challenge: Do other models yield the observed scaling law?

III. Flux-rope CMEs from the sun to 1 AU

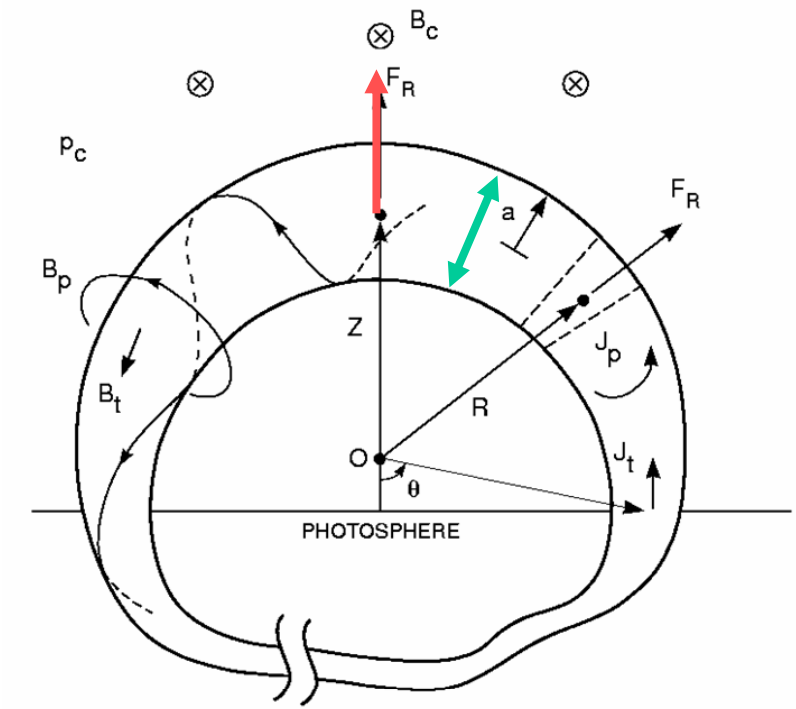
How well do we reproduce observed dynamics?

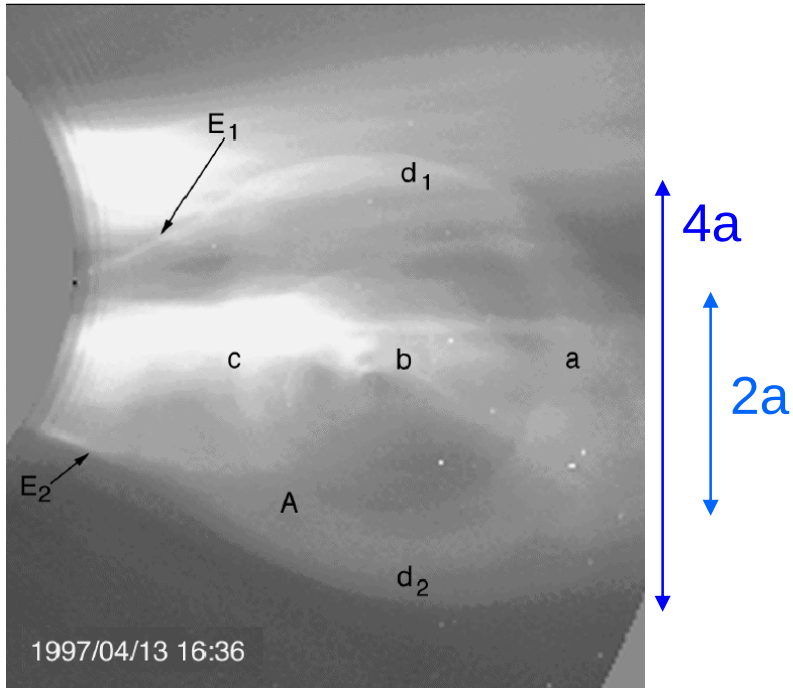
- Near sun position, velocity and morphology
- Transit time to 1 AU
- Magnetic cloud size, strength, and orientation

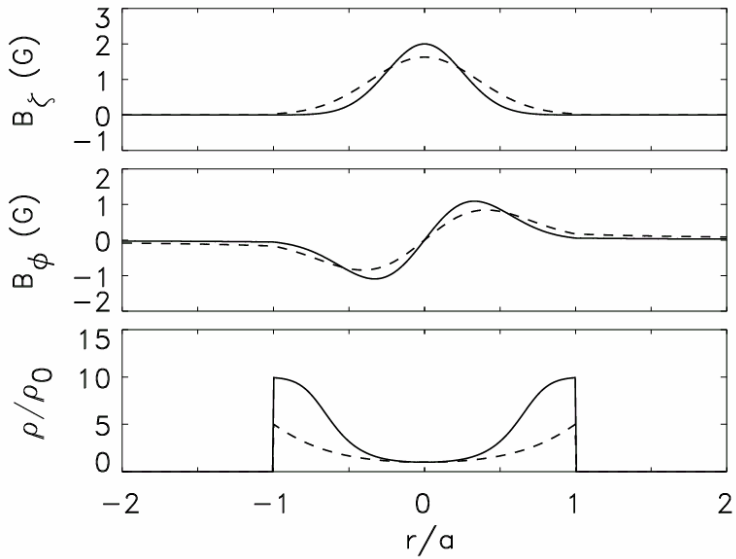
What can we predict?

- Ideally: magnetic cloud onset, size, strength and orientation

Flux Rope Model



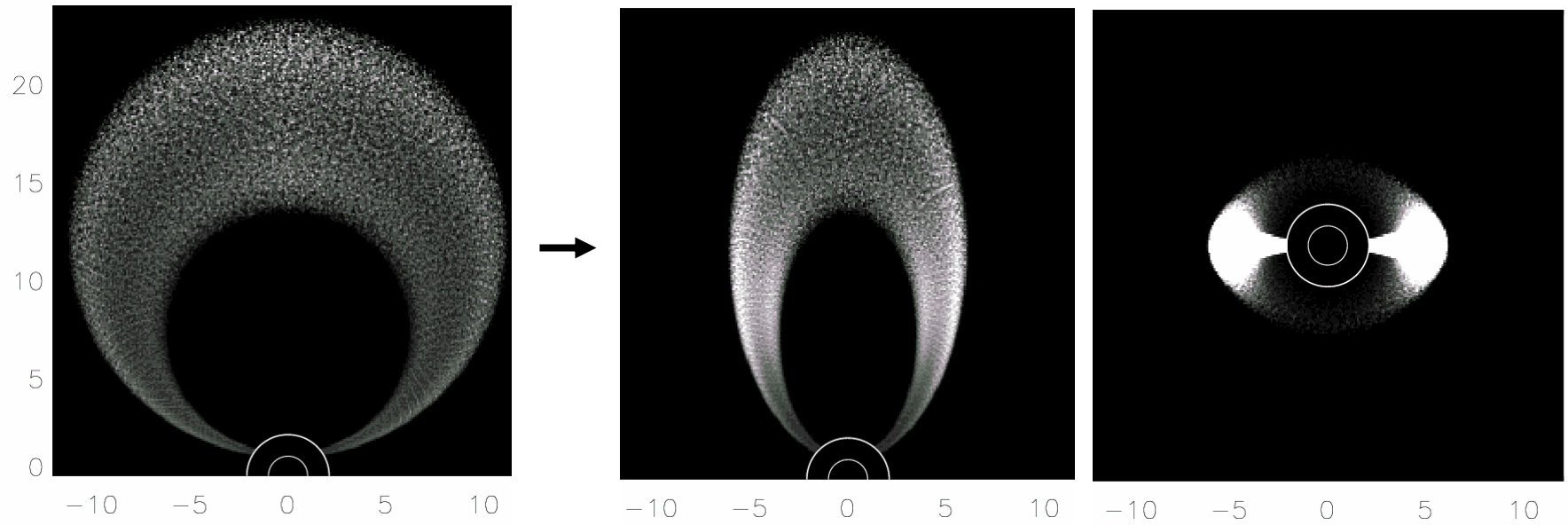




As in past studies, we hypothesize a flux-rope structure with a "hollow" internal density profile (Krall et al. 2004, unpublished).

Halo CMEs: an elliptically-shaped model flux-rope

To obtain a flux rope which reproduces CME dynamics and "looks like a CME" from all angles, we use an elliptical flux rope

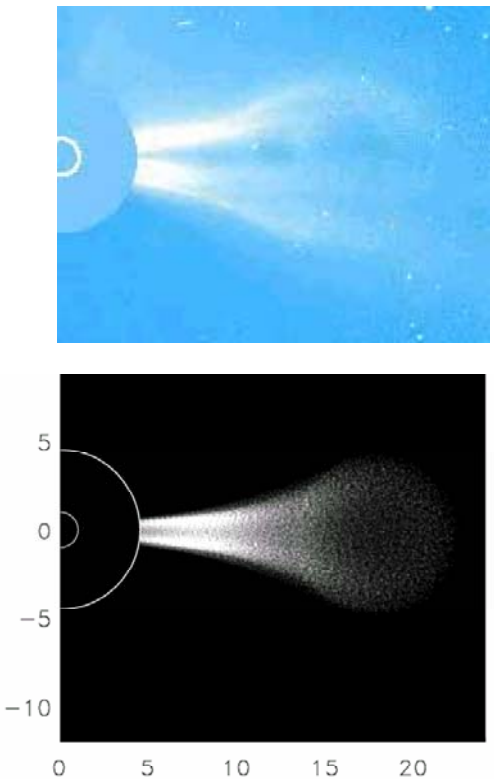


$$F_{JxB} \sim \Phi_p^2 \kappa^2$$

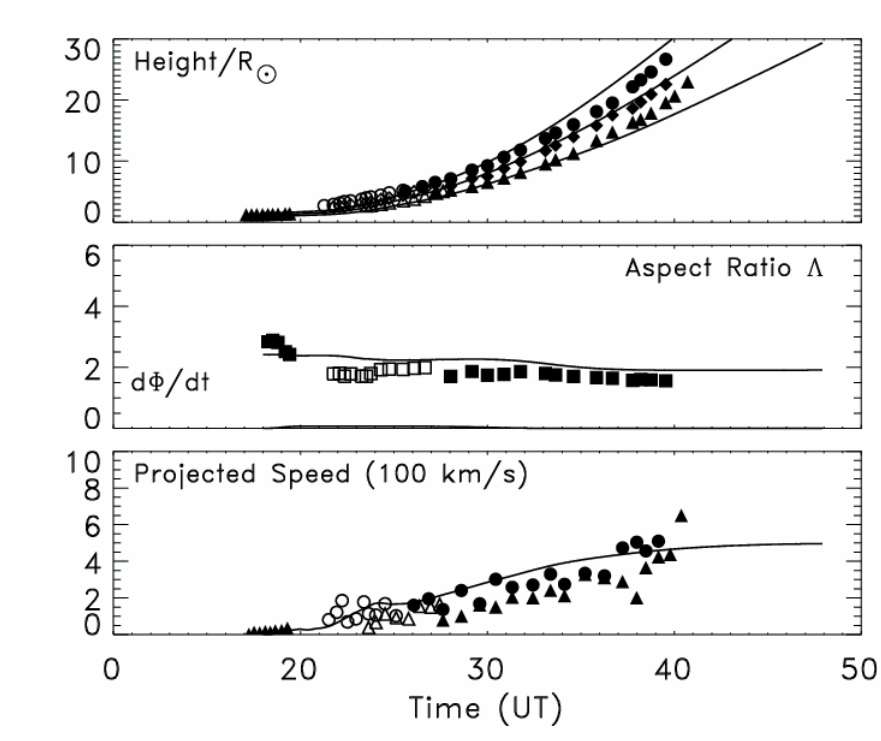
(JxB force is related to the local curvature)

Garren and Chen 1994 Phys. Plasmas

The elliptical flux rope model reproduces CME dynamics as in the circular model (model inputs differ somewhat)

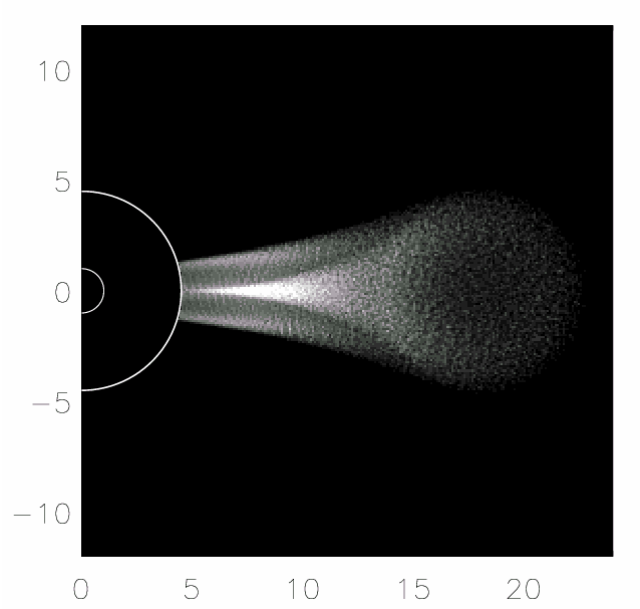


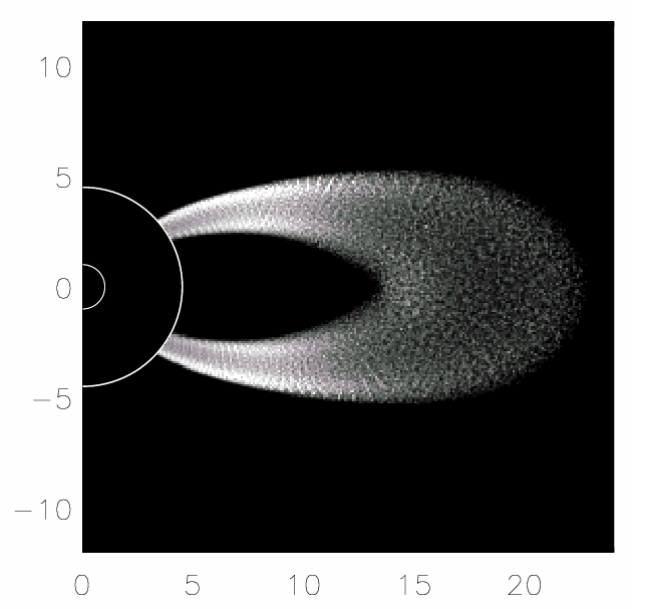
LASCO C3 and model
(1997/11/02 12:41 UT)



model/data comparison for 1997/11/01 CME
(data from Krall et al. 2001 ApJ)

The elliptical flux rope reproduces other observed morphologies

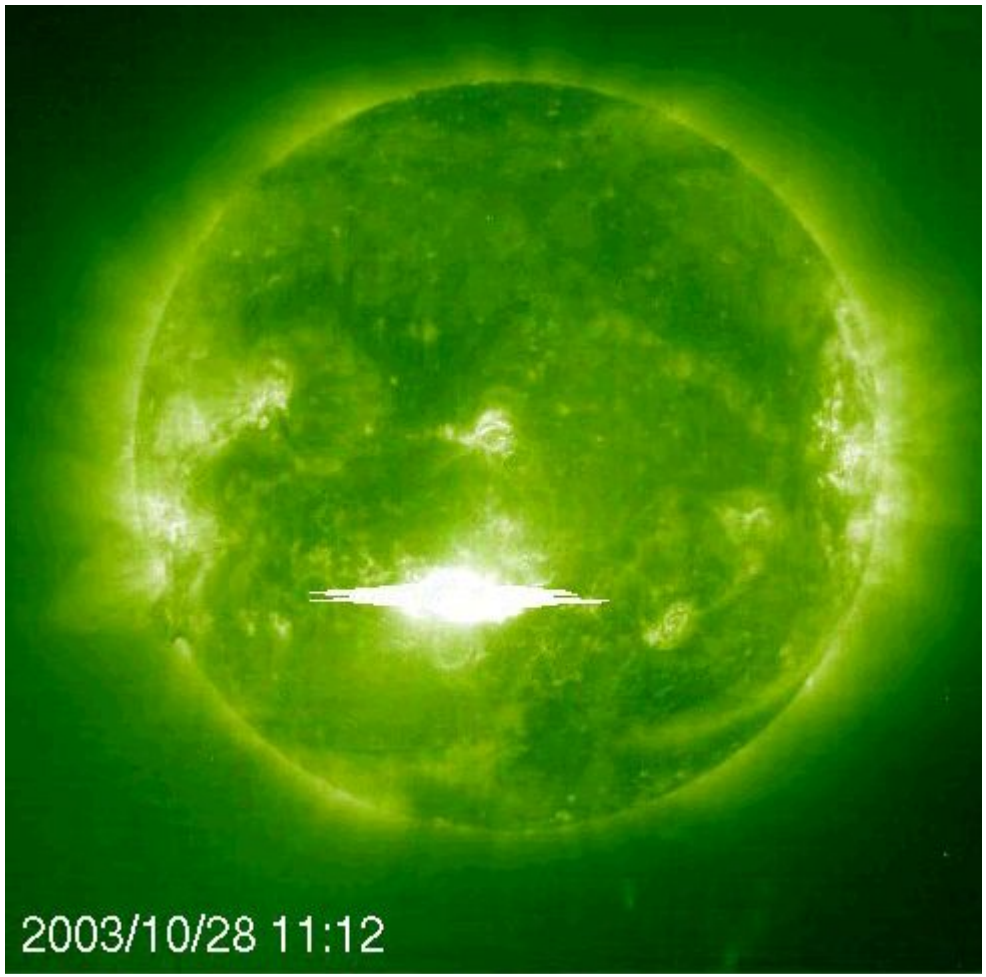


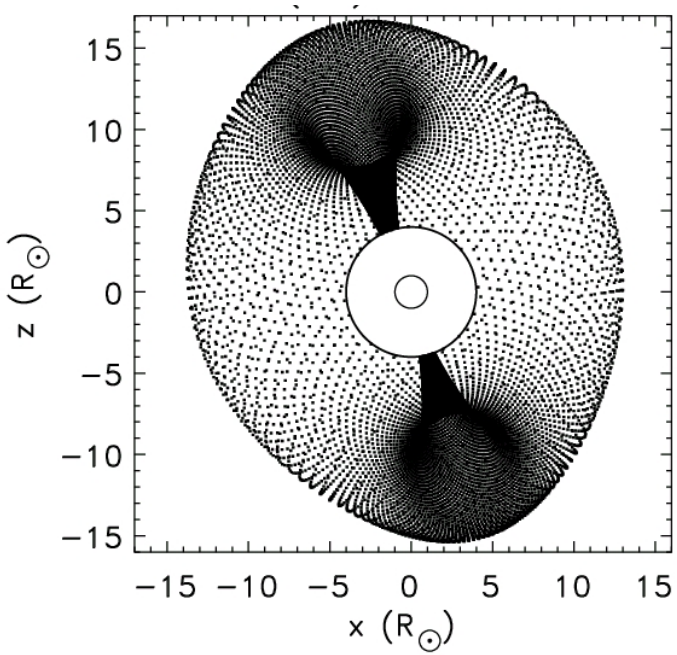


A slightly-tilted limb event (λ = 0, ϕ = 90, α = 10) looks like a “disconnection event” with a “bright ray”

With a larger tilt, (λ = 0, ϕ = 90, α = 50) the “disconnection” and the “bright ray” are gone.

October 28, 2003





EIT image, LASCO/C3 image, scatter-plot of outer flux surface

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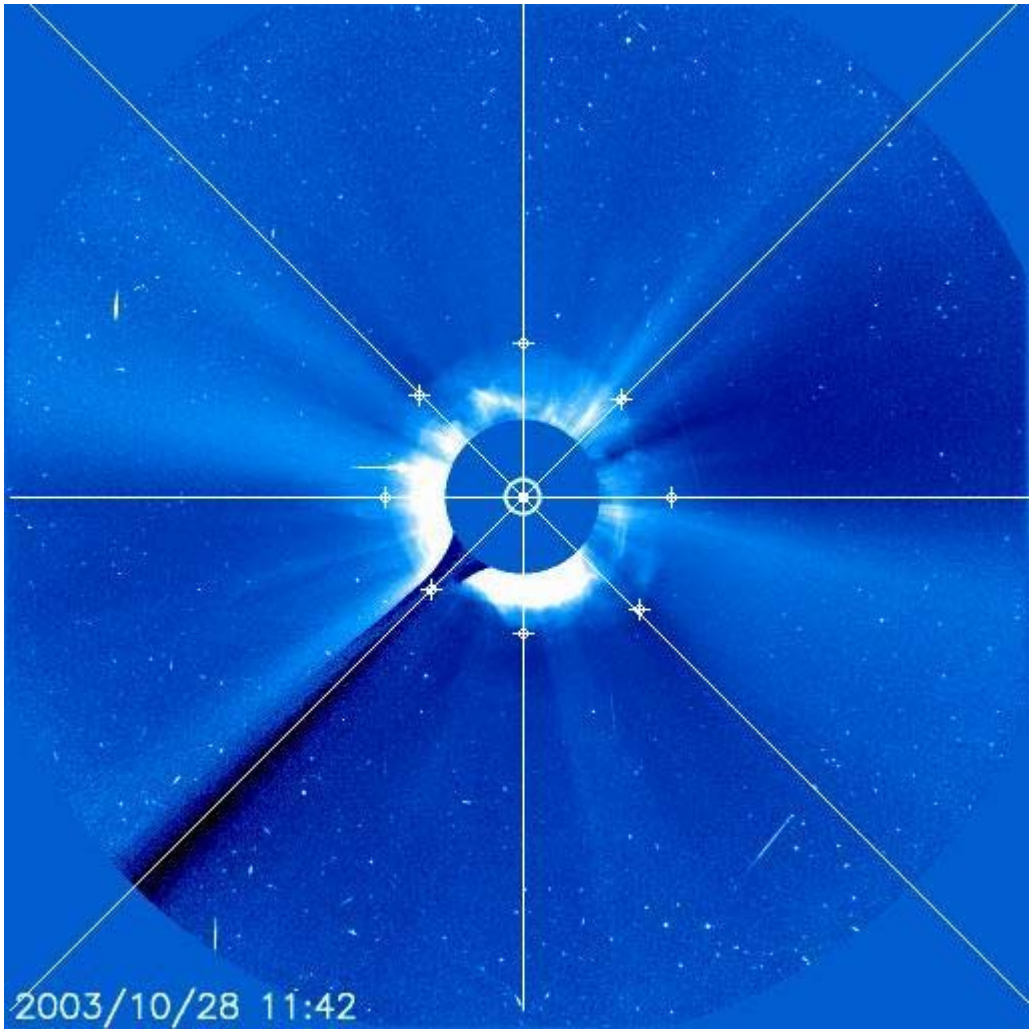

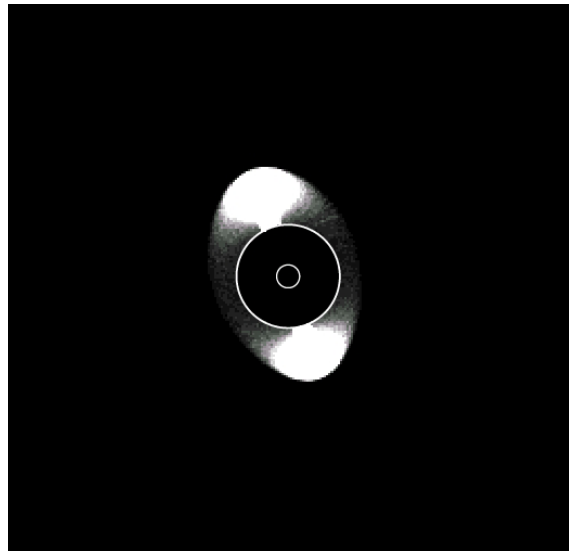

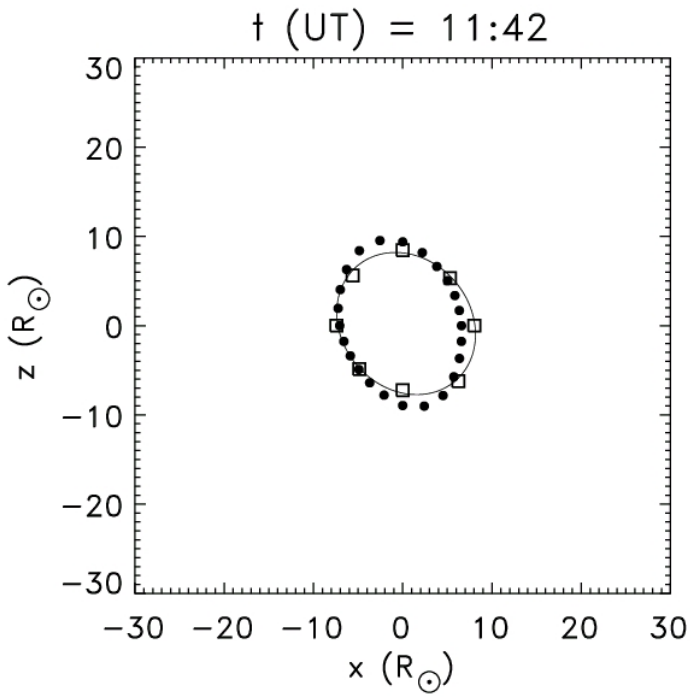

Measurements by Vasyl Yurchyshyn (BBSO)

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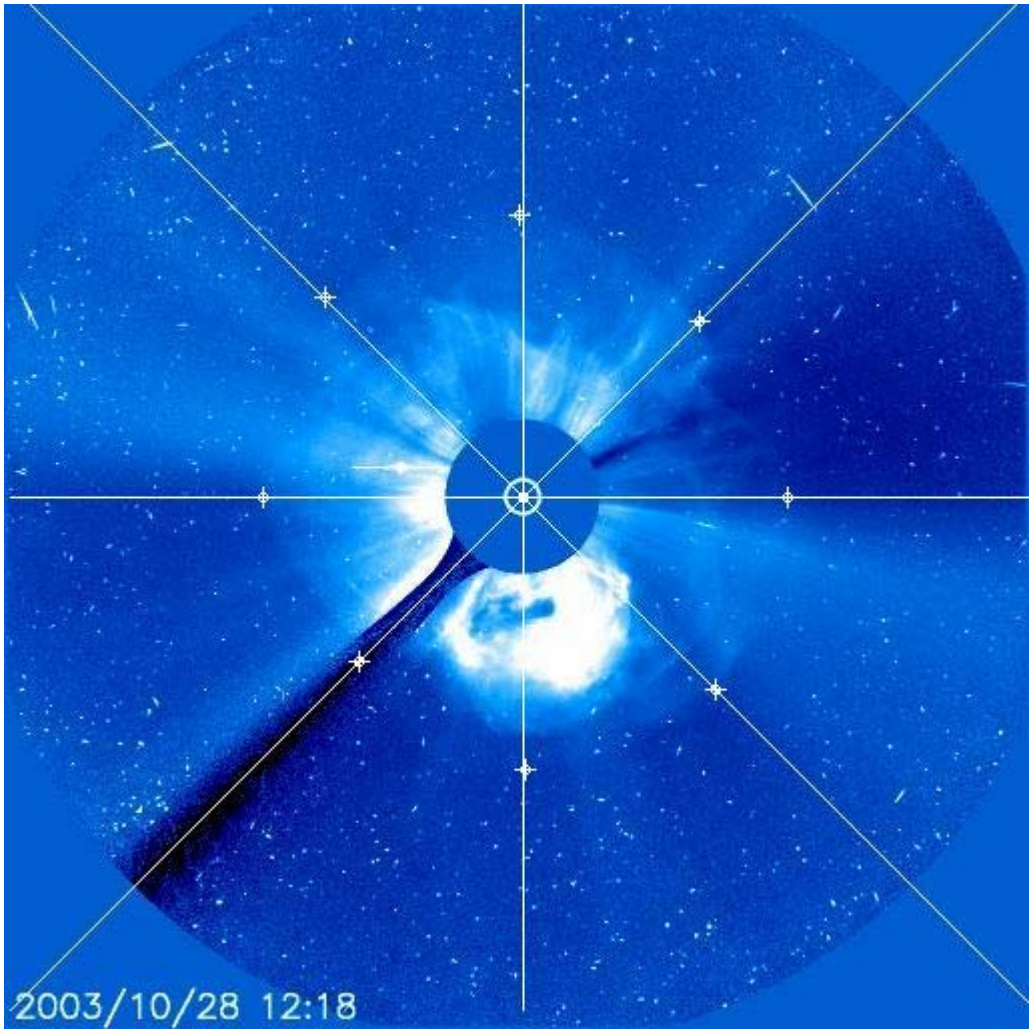

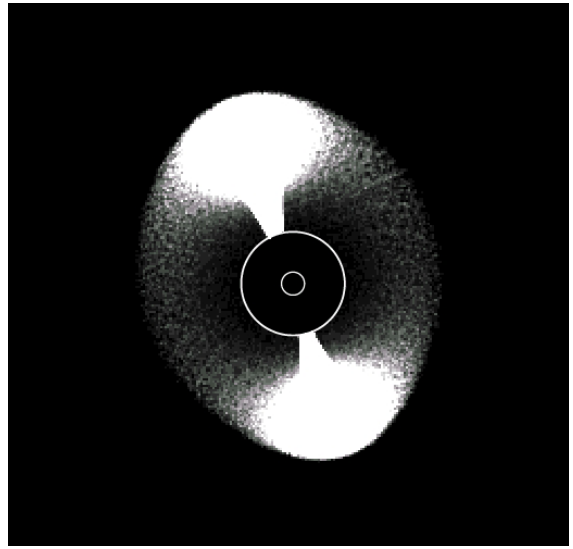

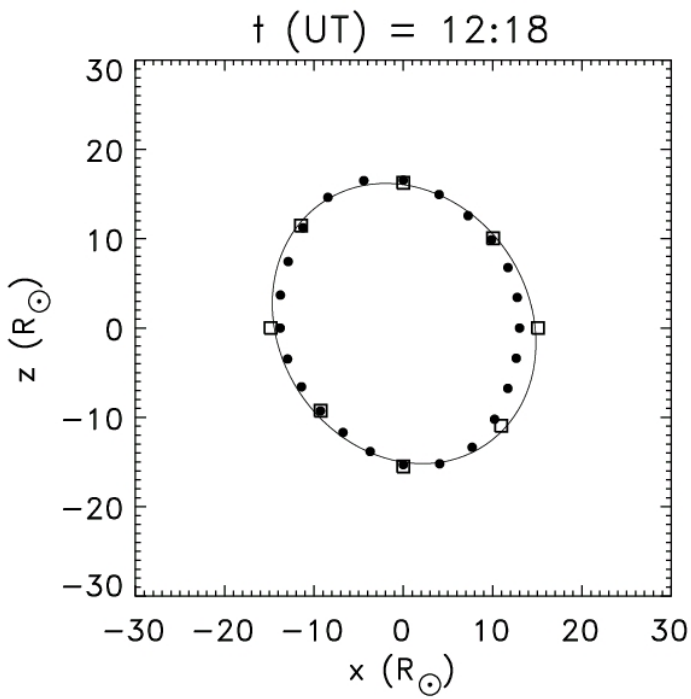

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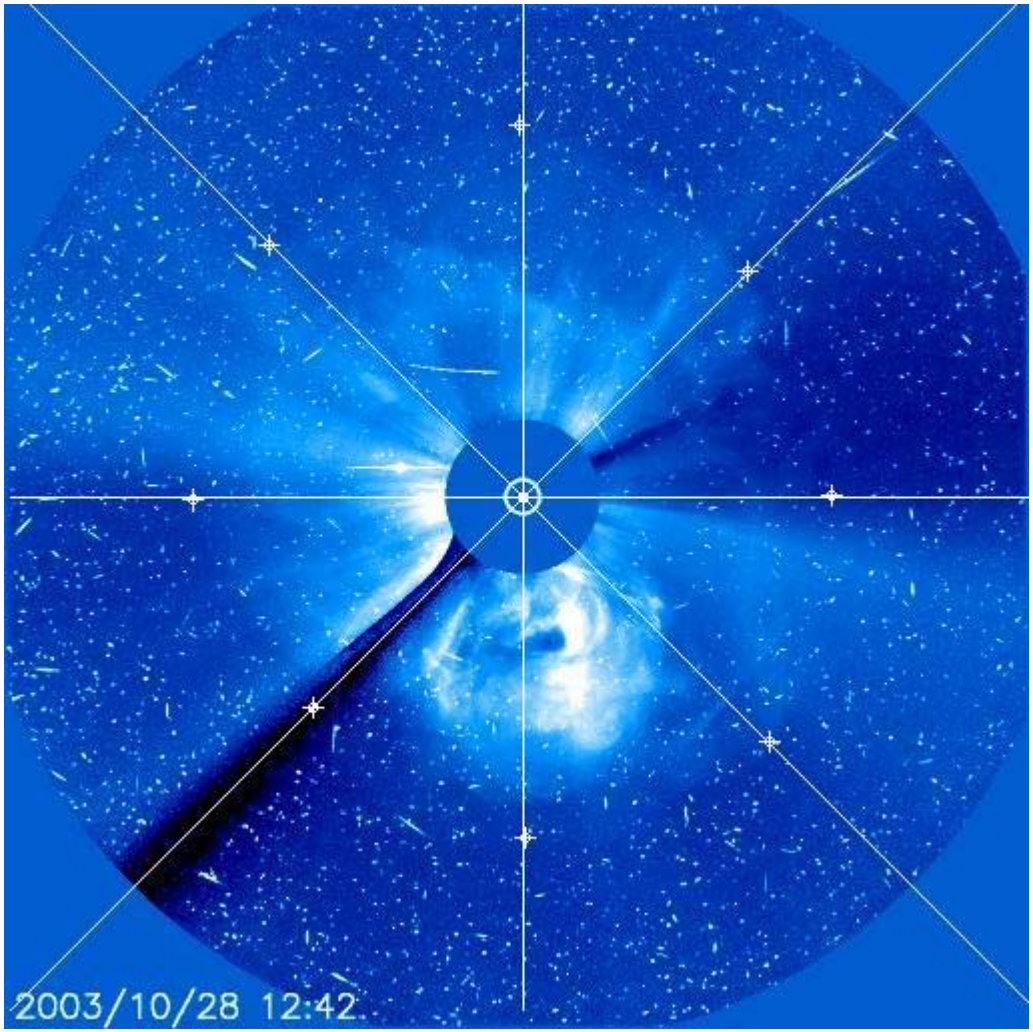
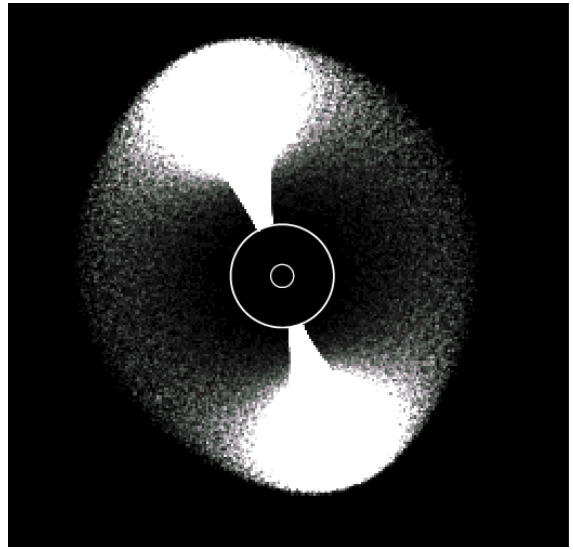
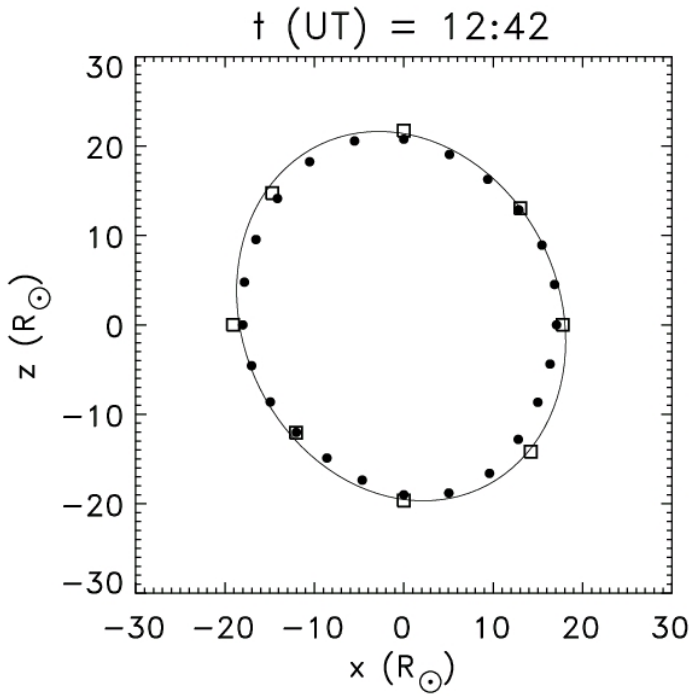
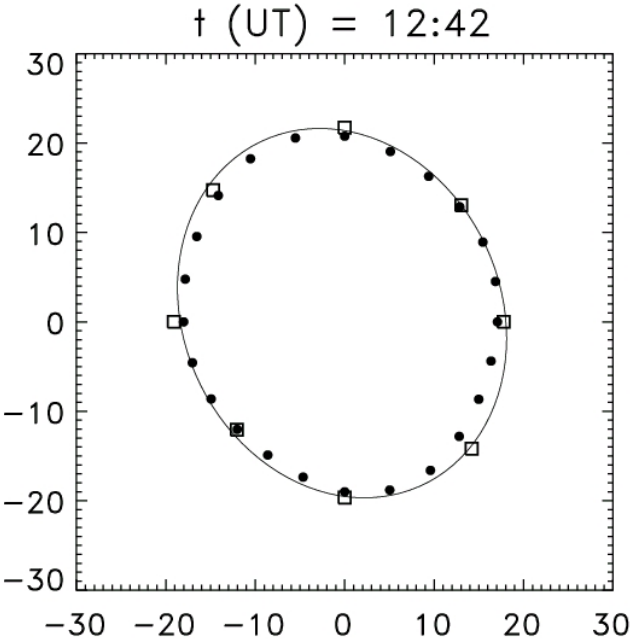
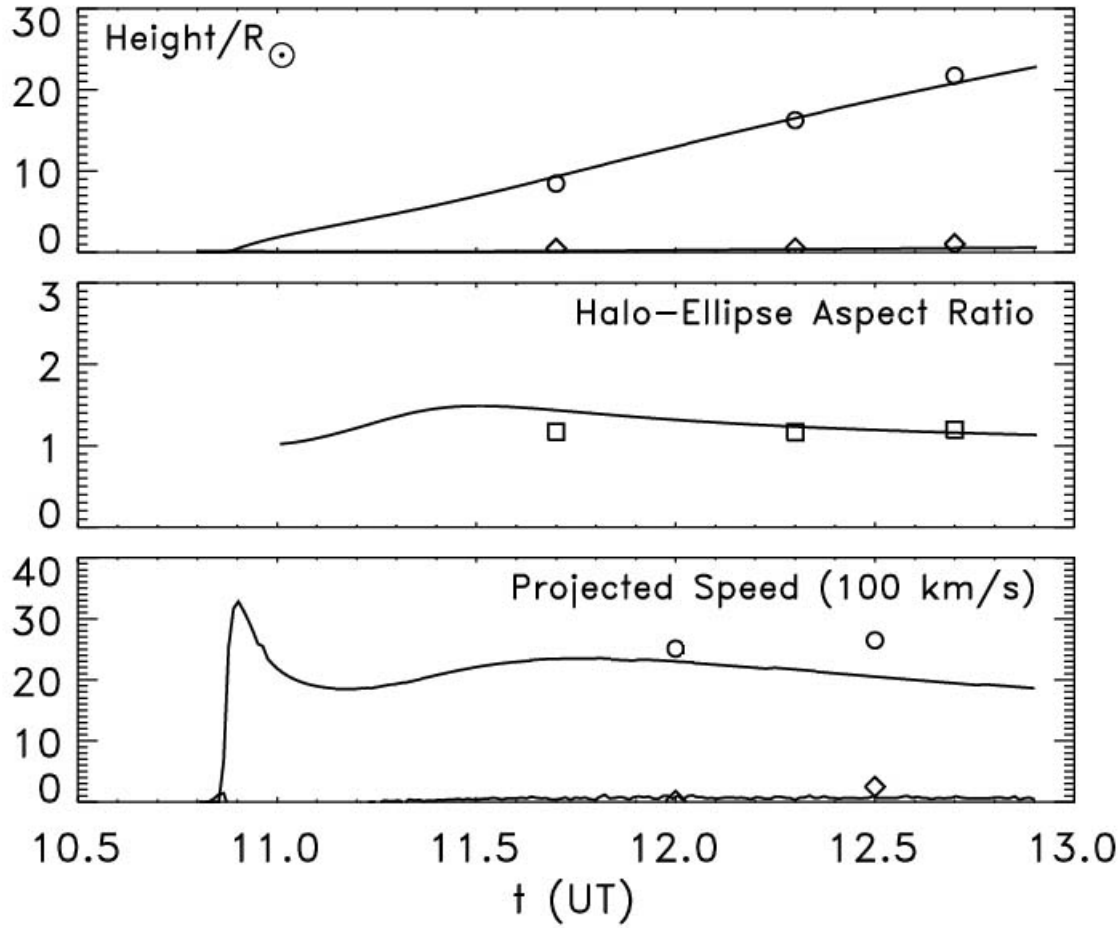




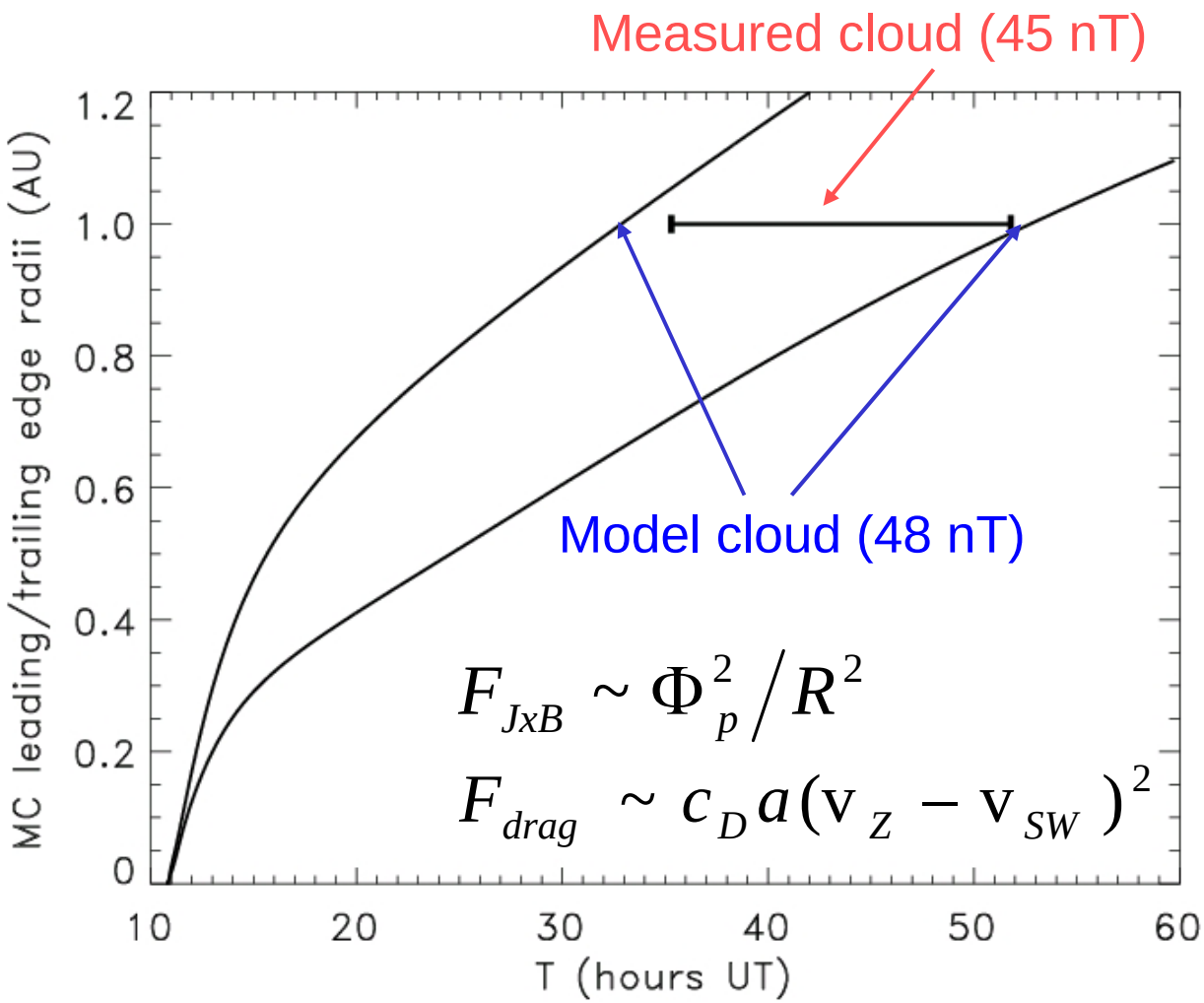


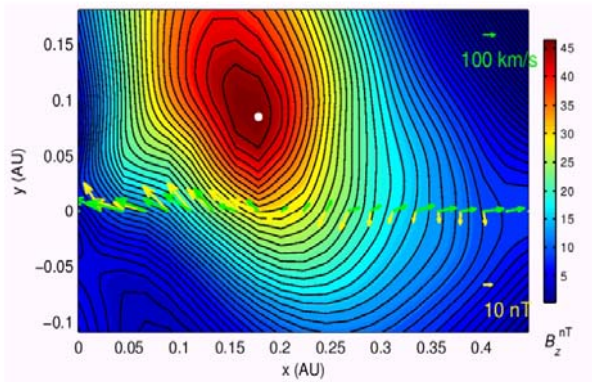
October 28, 2003 – Near Sun Dynamics





October 28, 2003 – Expansion to 1 AU





Ace reconstruction from Yurchyshyn et al., SPD 2004 Meeting

Flux-rope CMEs from the sun to 1 AU

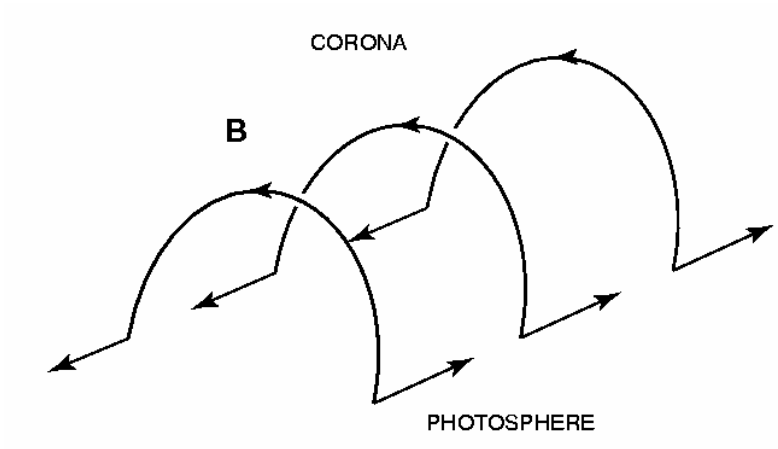
How well do we reproduce observed dynamics?

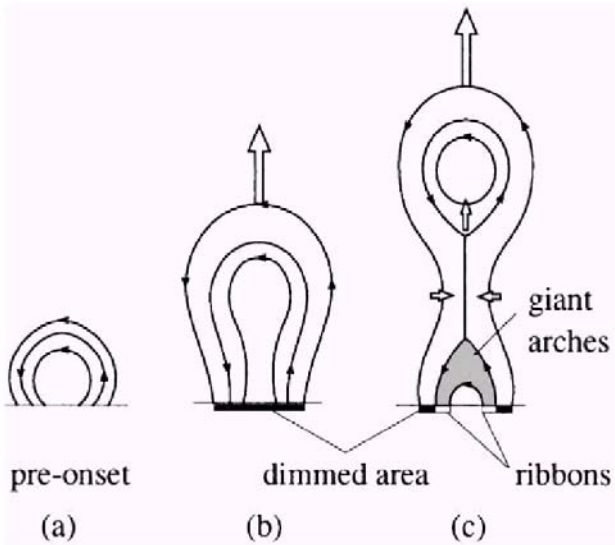
- Near sun position, velocity and morphology
- Transit time to 1 AU
- Magnetic cloud size, and strength

What can we predict?

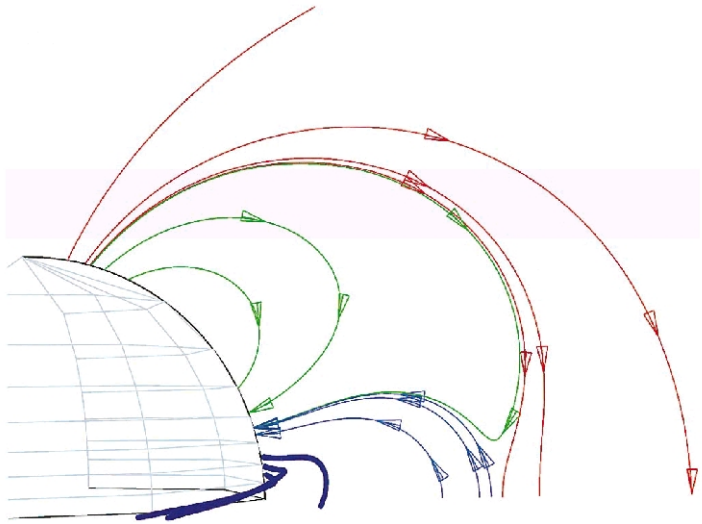
- General magnetic cloud parameters
  (we need to simulate more events)

IV. Macroscopic magnetic reconnection: is it needed?



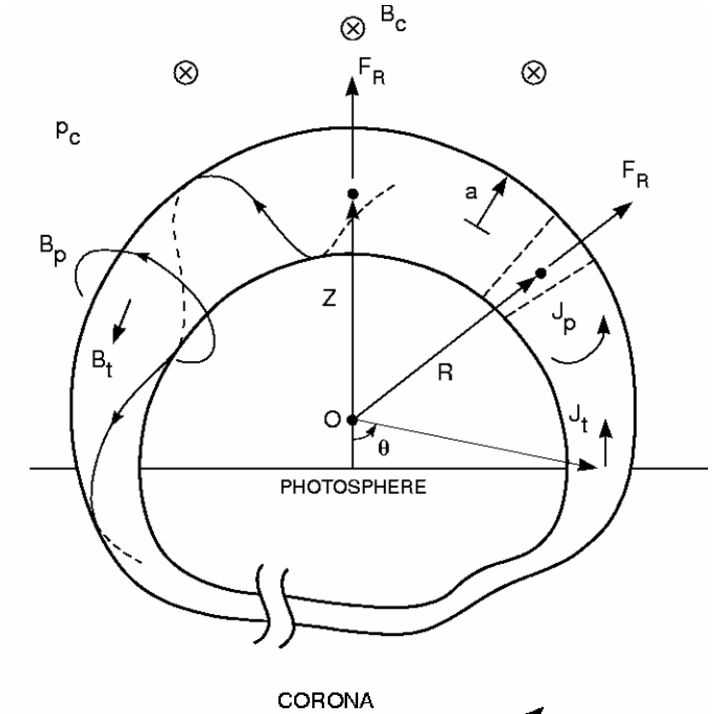


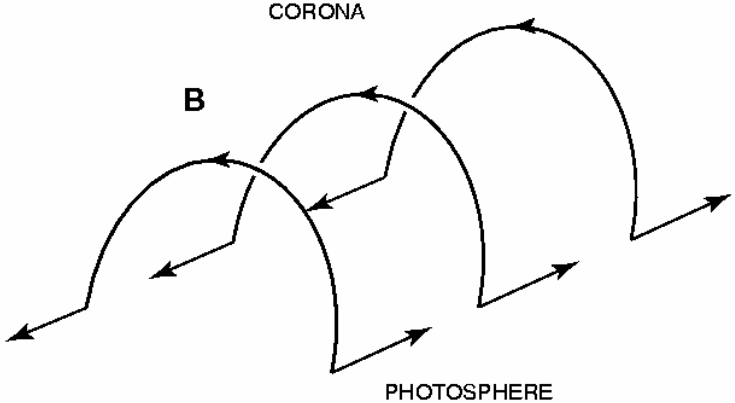
Forbes and Lin (2000)

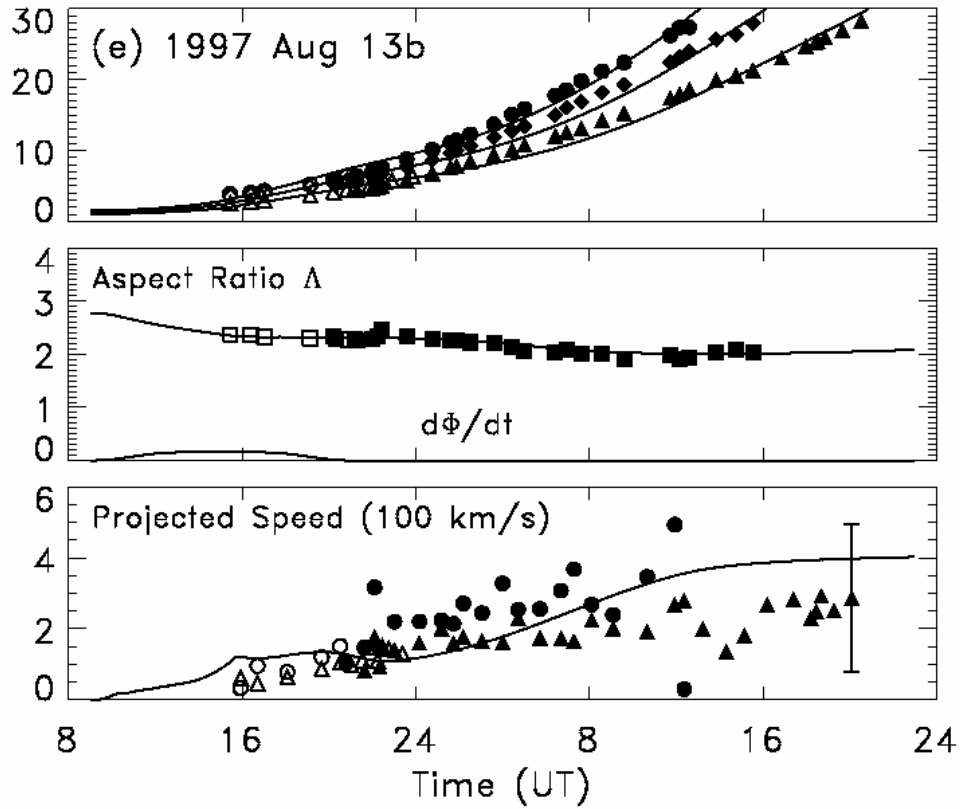


Antiochos et al. (2000)

Open question: how does the flux get into the flux rope?



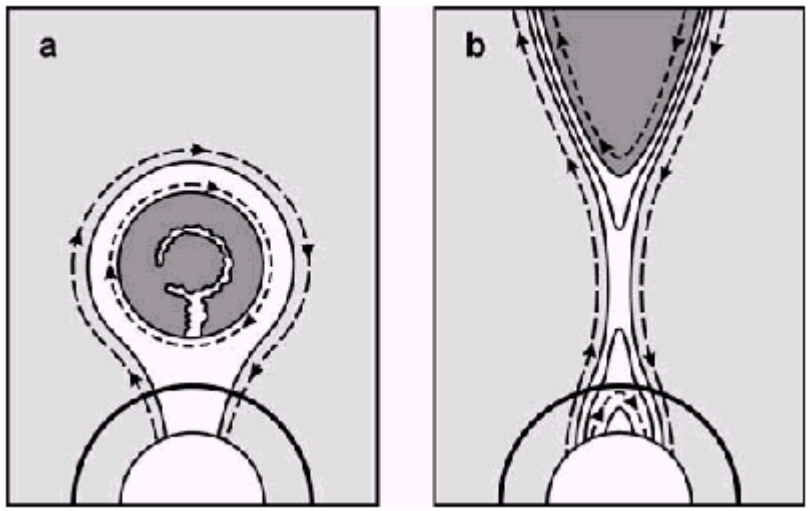




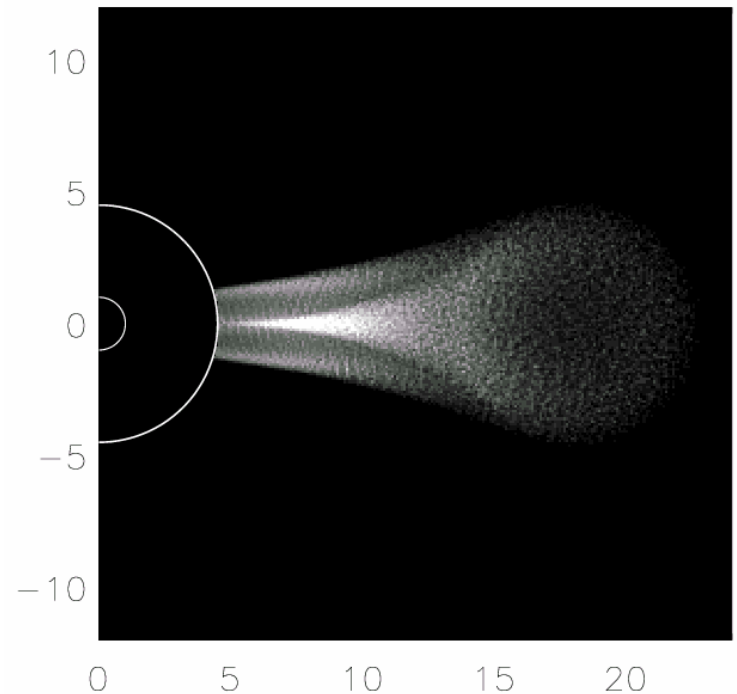
In corona:

$$v_{Ti}/\Omega_i \sim c/\omega_p \sim 10\,\mathrm{m}$$

“Disconnection events”

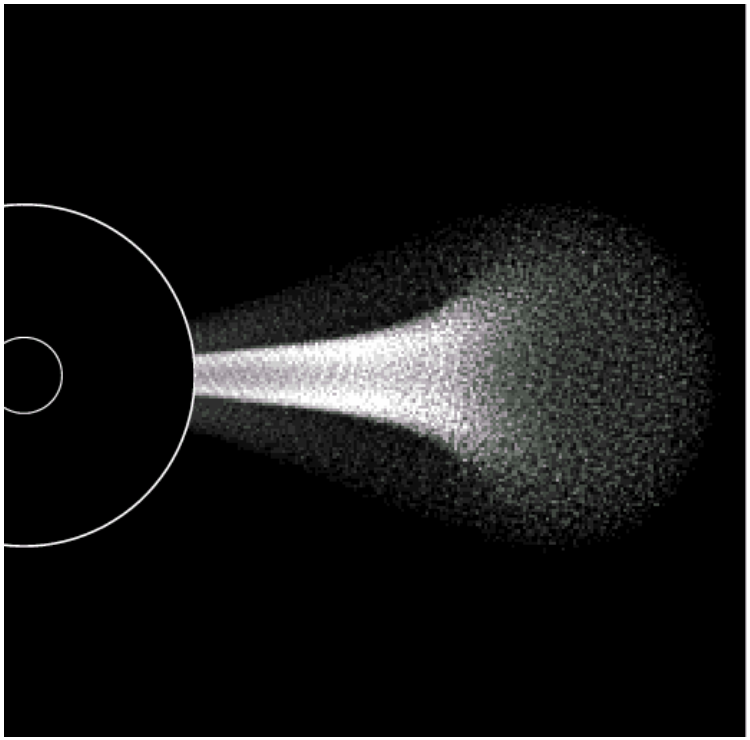


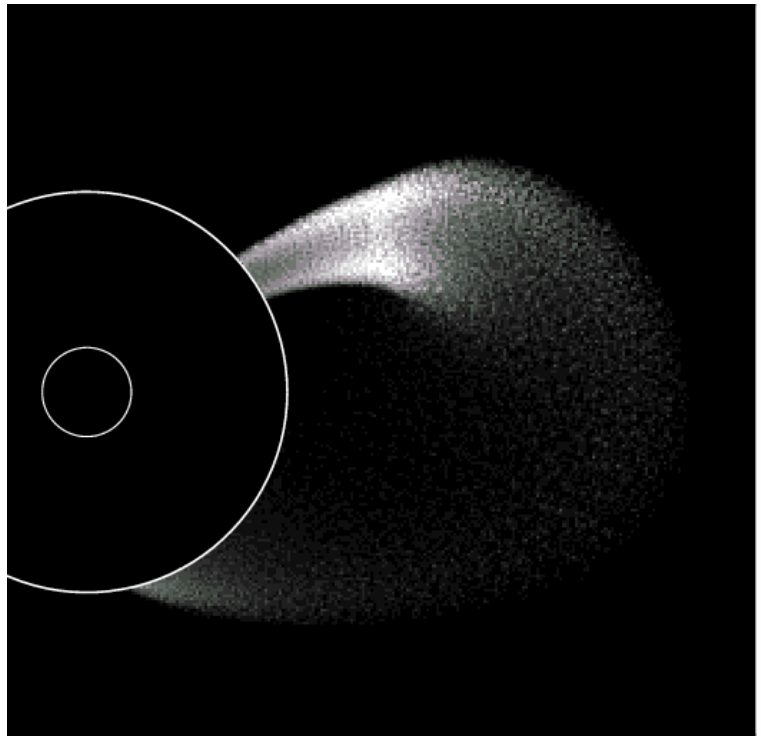
Webb et al. 2003, JGR, 108 (A12), 1440



A slightly-tilted limb event (λ = 0, ϕ = 90, α = 10) looks like a “disconnection event” with a “bright ray”

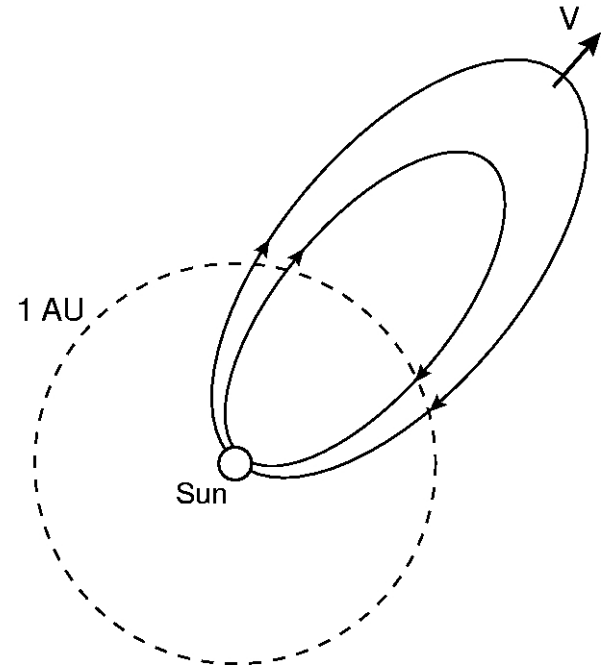
“Disconnection events”





Thomson scattering favors the plane of the ecliptic;
a flux rope which is far from the limb has one leg highlighted

“Flux Catastrophe”



$$U_t \sim U_0 t_0 / t$$

For N flux ropes, each separated by δt_o $\quad \delta = \delta t_0 / t_0$

$$U_n \approx U_0 t_0 / [t_0 + (N-n)\delta t_0]$$

$$U_t \sim \sum_{n=1}^{N} \frac{U_0}{1+(1-n)\delta} \quad \text{diverges as } \log(N)$$

$$U_t \sim \sum_{n=1}^{N} \frac{U_0}{[1+(1-n)\delta]^{1+\eta}} \quad \text{converges for} \quad \eta > 0$$

No energy catastrophe for nonzero dissipation

V. Summary

Flux rope model continues to capture basic CME physics

- Near-sun acceleration profile
- Morphology
- Dynamics out to 1 AU

Challenges to other models:

- Reproduce and explain the acceleration scaling
- Reproduce the dynamics out to 1 AU

Open question:

- Does macroscopic magnetic reconnection occur?

End

Flux Rope Model

$$M\frac{\partial^2 Z}{\partial t^2}=\frac{I_t^2}{c^2R}[\ln(\frac{8R}{a})-1+\frac{\xi_i}{2}$$

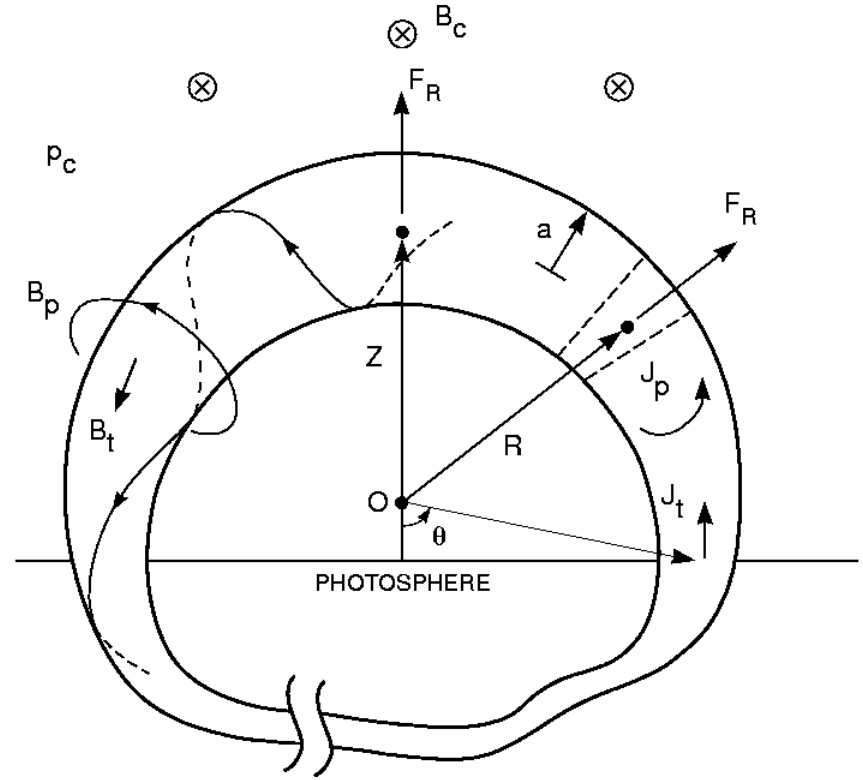
$$-\frac{1}{2}\frac{\overline{B}_t^2}{B_p^2}-\frac{2R}{a}\frac{B_{\perp,c}}{B_p}$$

$$+\frac{1}{2}\beta_p]$$

$$-[M_p+\pi a^2(\rho_i-\rho_c)]g(z)$$

$$-c_D n_c m_p a(\mathrm{v}_Z-\mathrm{v}_c)\left|\mathrm{v}_Z-\mathrm{v}_c\right|$$

$$\frac{\partial^2 a}{\partial t^2}=\frac{I_t^2}{Mc^2a}(\frac{B_t^2}{B_p^2}-1+\beta_p)$$



Chen, J. 1996, JGR, 101, 27499
Krall J., et al. 2000, ApJ, 539, 964